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In-Beam Reactions and Spectroscopy at Early FRIB

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Outline

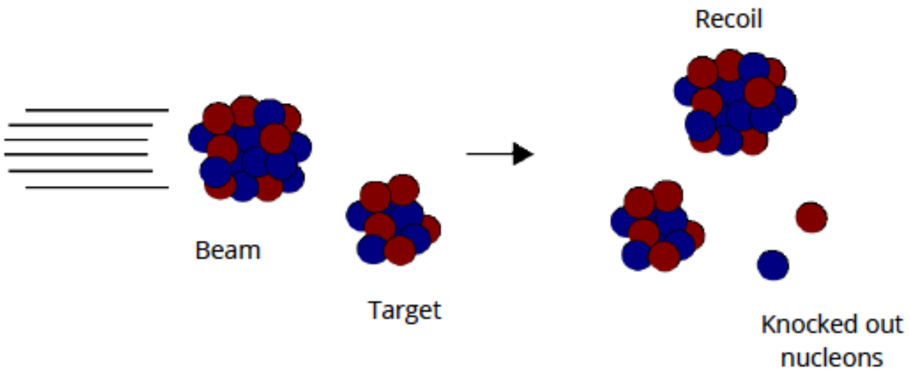
- Nucleon knockout
  - KO on Be/C targets
  - (p,2p)/(p,pn)/… on LH_2 target
- Coulomb excitation and inelastic proton scattering
- Where on the Segre chart?

Direct Reactions and In-Beam Gamma Spectroscopy

Powerful and frequently used approach to investigating level schemes and wavefunctions (C^2S)

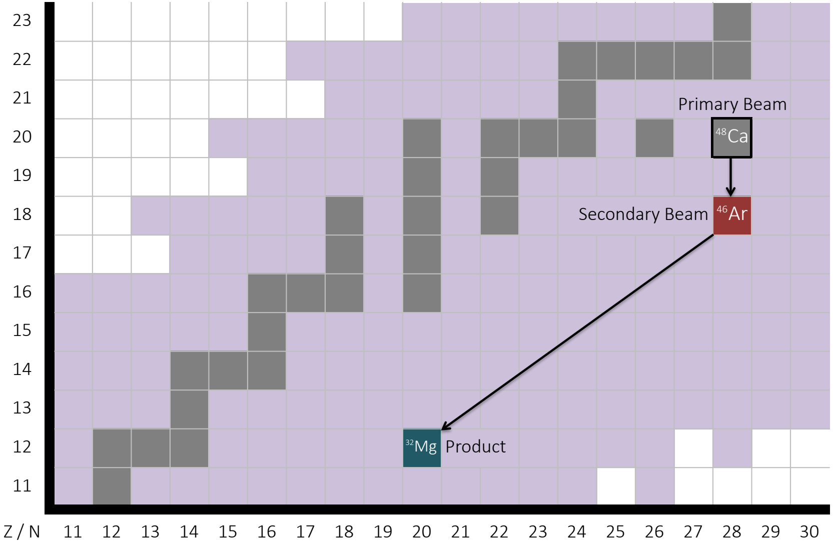
- Focus on reactions at ‘intermediate energy’ – for transfer reactions etc. see presentations in week 1 (Pain, Lubna)
- Two scenarios – (a) use reactions as a tool to populate level schemes;

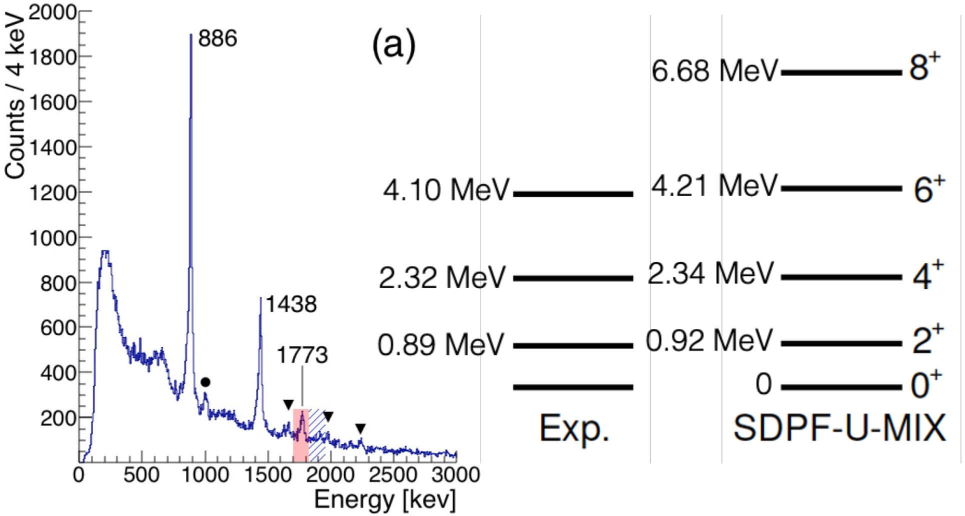
  (b) interpret reaction quantities (cross-sections) to gain structure insight
- For (b) we consider direct reactions – the reaction theory is rooted in the eikonal approximation



In-Beam Spectroscopy – Level Schemes

Secondary fragmentation for a level scheme with statistical population





- In order to populate different states, take advantage of different approaches to populating the nucleus – ‘high’ spin states populated in secondary fragmentation
- Statistical descriptions of final state population $P_k^s = N(2j_k + 1)e^{-E_k^*/T}$

HLC *et al.*, PRC **93**, 031303 (2016).
A. Obertelli *et al.*, PRC **73**, 044605 (2006).

Nucleon knockout reactions

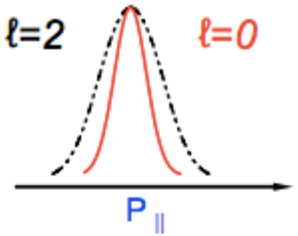
Nucleon removal on a light nuclear target (Be, C)

Intermediate energy beams (> 50 MeV/nucleon)

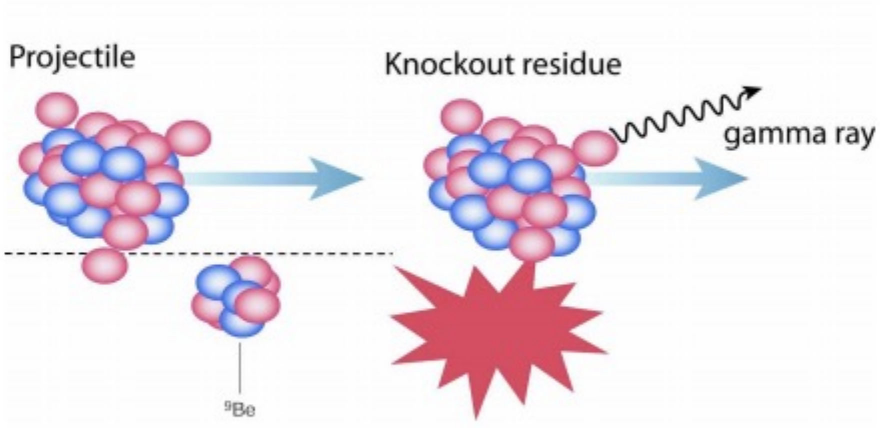
- Sudden approximation + eikonal approach for reaction theory

Spectroscopic strengths --> exclusive cross-sections

- Populated states in A-1 residue provide detailed measure of beam structure



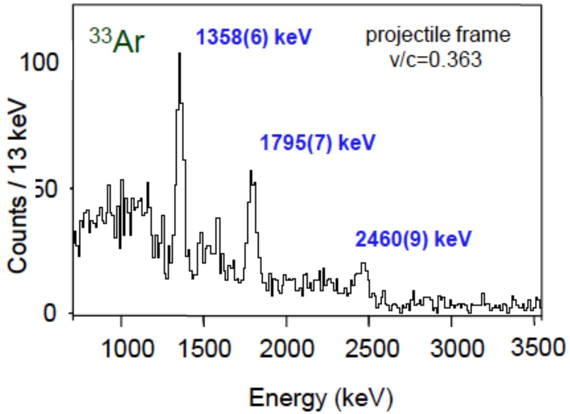
residue moment distribution
→ ℓ-value of knocked-out n

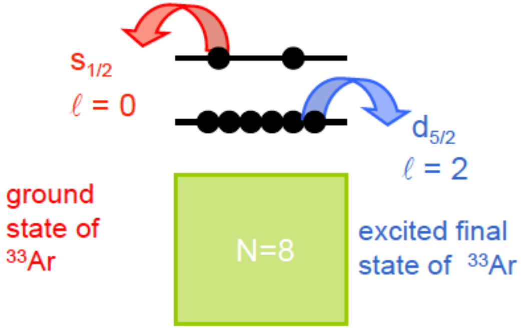


Theoretical cross-section

$$\sigma(j^\pi) = \left(\frac{A}{A-1}\right)^N \underbrace{C^2 S(j^\pi)}_{\text{Structure theory}} \overbrace{\sigma_{sp}(j, S_N + E_x[j^\pi])}^{\text{Reaction theory}}$$

Neutron knockout – ^{9}Be(^{34}Ar, ^{33}Ar)X

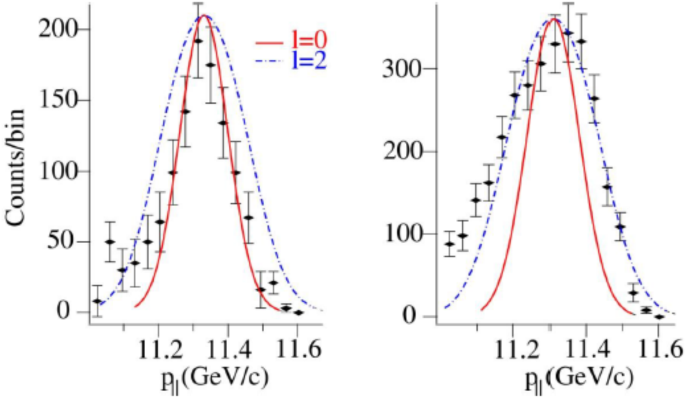




ground state of ^{33}Ar

excited final state of ^{33}Ar

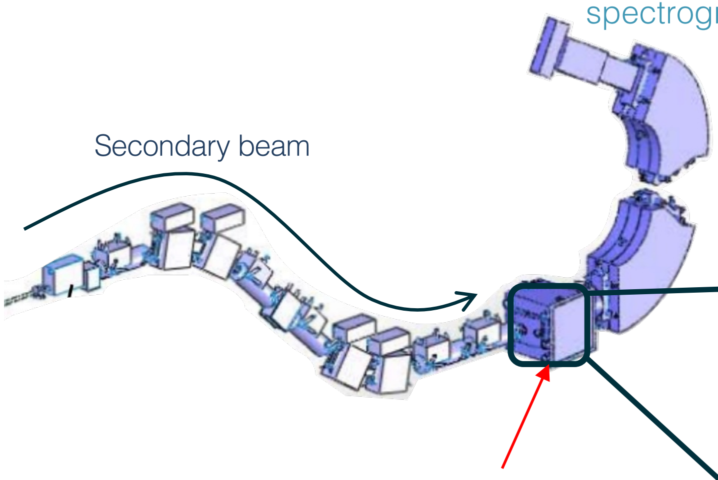
	BR (%)	σ_{exp} (mb)	C^2S_{exp}
$1/2^+$	30.2(46)	4.7(9)	0.38(6)
$3/2^+$	20.2(44)	3.2(8)	0.36(9)
$5/2^+$	31.7(31)	4.9(7)	0.56(8)
$(5/2^+)$	17.9(30)	2.8(6)	>0.34(7)



A. Gade et al., PRC **69**, 034311 (2004).

Experimental Setup

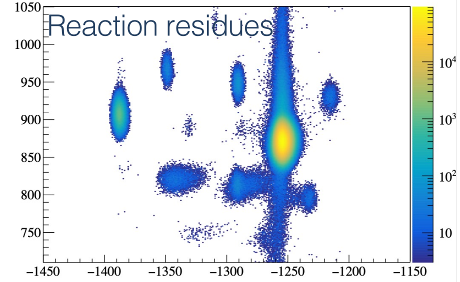
Secondary Target + Gamma-Ray Detection + Spectrometer

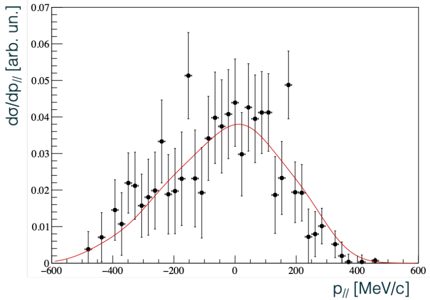


S800
spectrograph

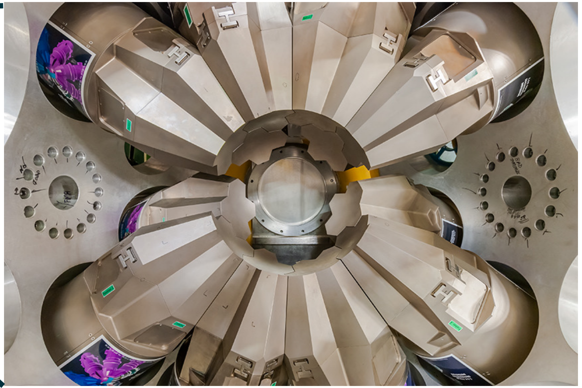
Secondary beam

Secondary target (Be/C/LH$_2$…)





4 quads at 58˚, 8 quads at 90˚



https://people.nscl.msu.edu/~noji/gret_12det

Experimental Setup

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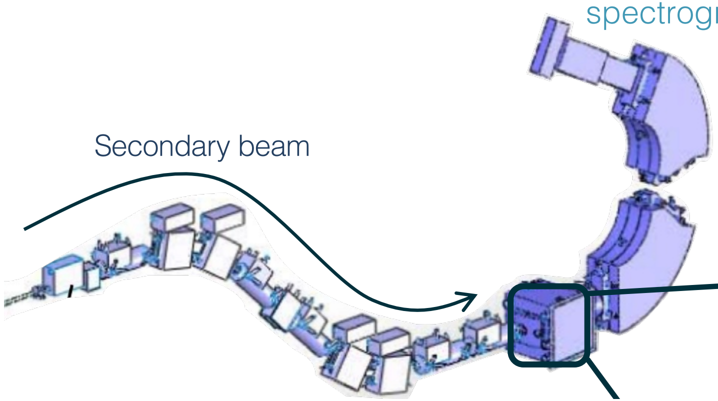
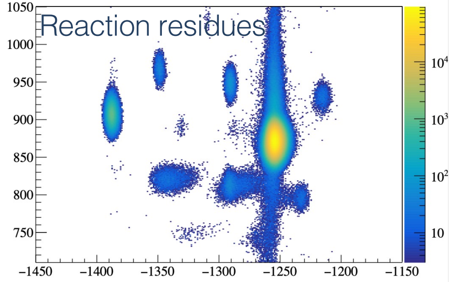
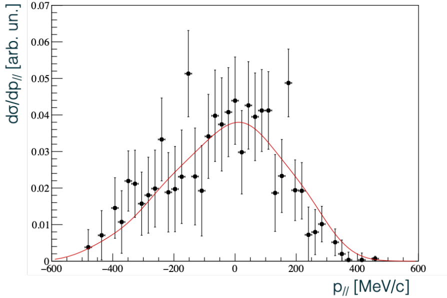
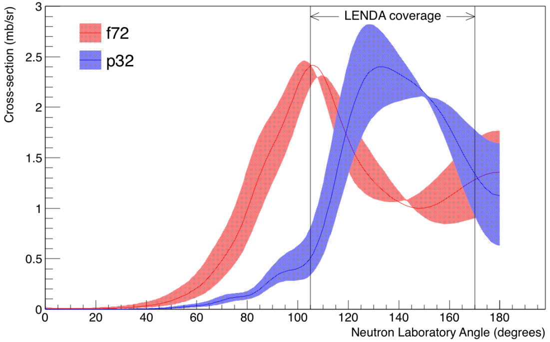


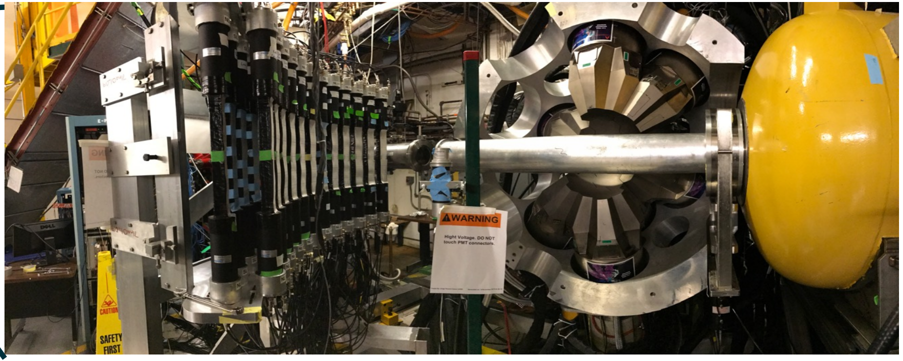
S800
spectrograph

Secondary beam





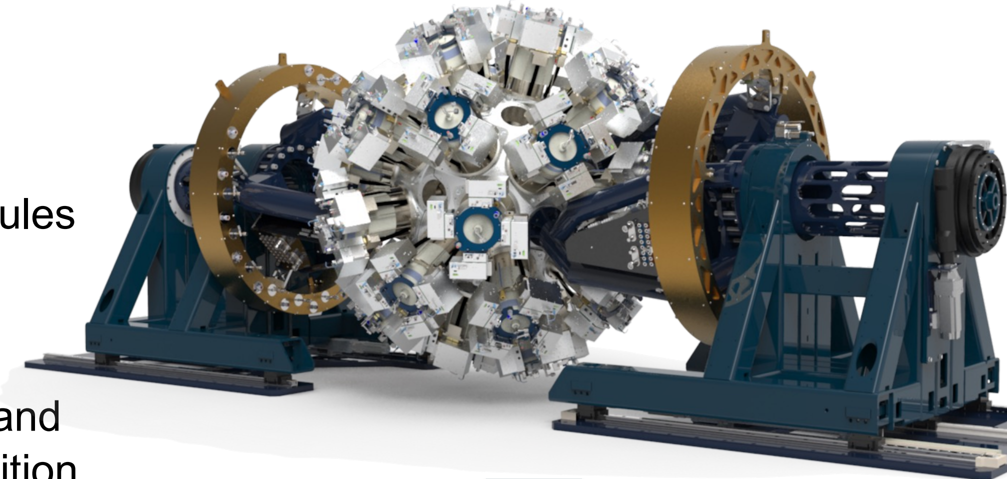


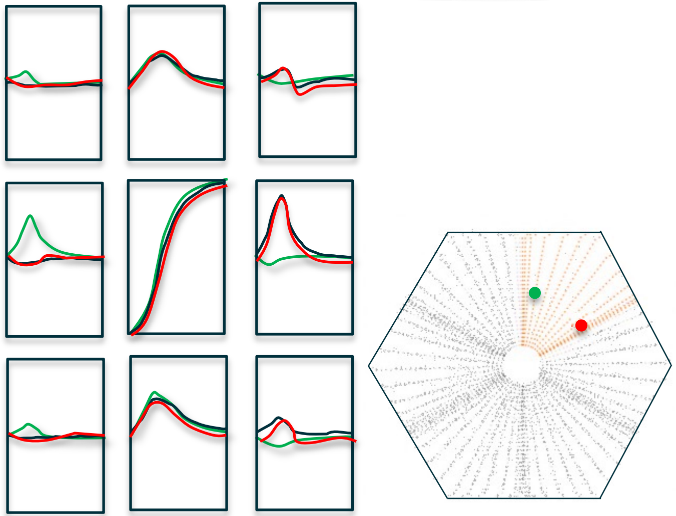


In addition to gamma-ray detection can have additional auxiliary detectors.

GRETA

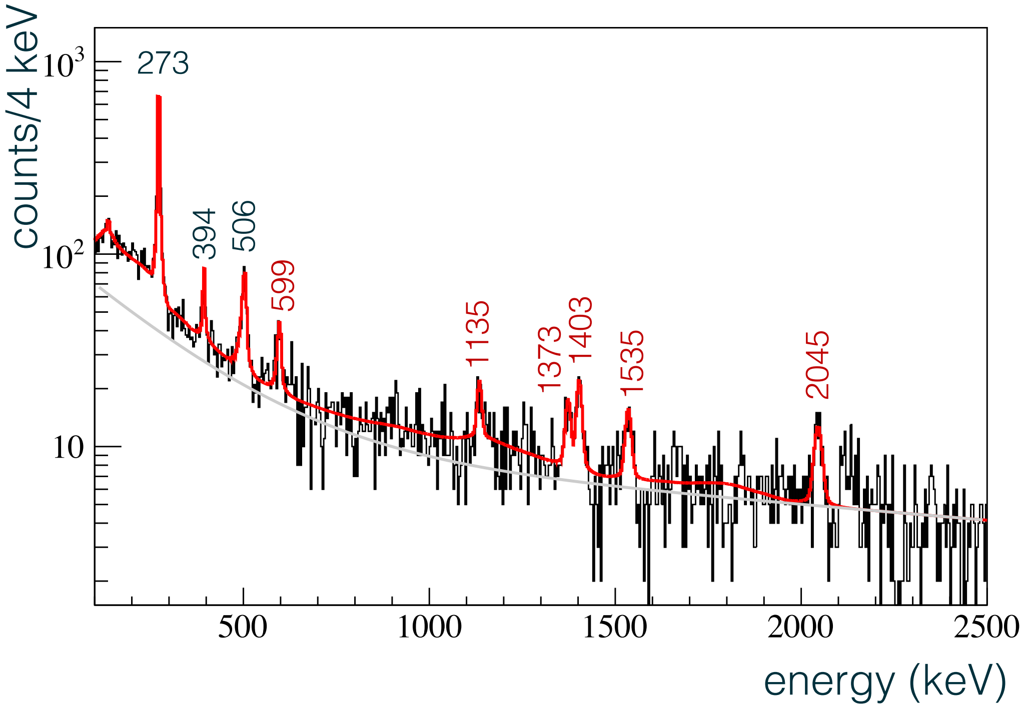
- GRETA will have 30 Quad Detector Modules to cover >80% of the full solid angle surrounding a target
- Its design provides the unprecedented combination of full solid angle coverage and high efficiency, excellent energy and position resolution, and good background rejection (peak-to-total) needed to carry out a large fraction of the nuclear science programs at FRIB.
- Unmatched resolving power will enable further push to the driplines and other spectroscopic frontiers
- **Will be coupled to the S800, HRS and other auxiliary detector systems at ReA**

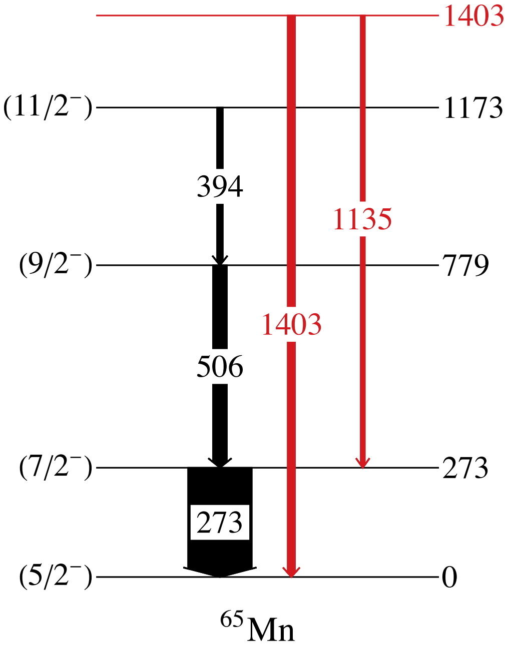




Example: Proton Knockout Near N=40

^{66}Fe(-1p)^{65}Mn with a Be target (among the last experiments at NSCL)

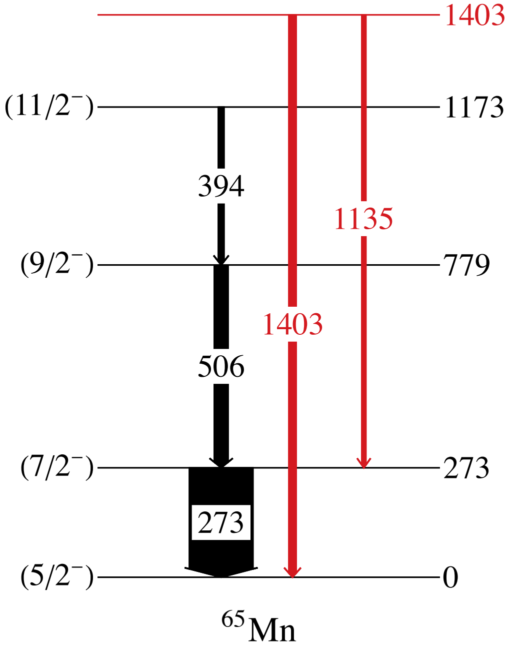




Liu *et al.*, PLB **784**, 392 (2018).
C. Porzio, HLC *et al.*, to be published.

Example: Proton Knockout Near N=40

^{66}Fe(-1p)^{65}Mn with a Be target – $f_{7/2}$ proton removal



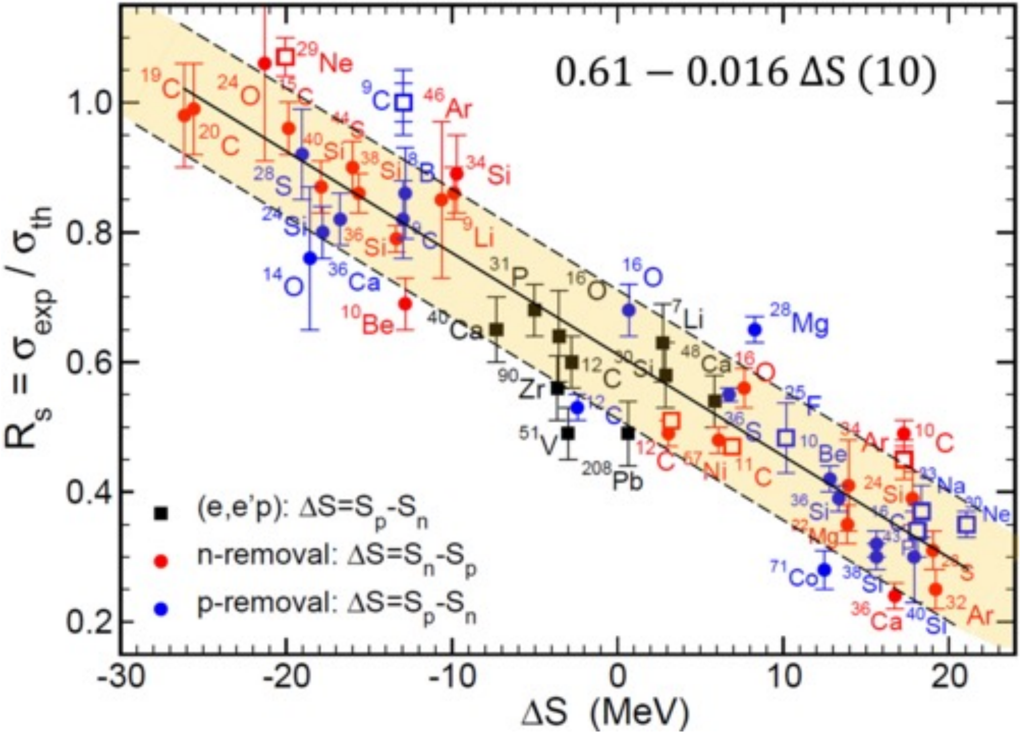
Final State	C²S SM	C²S Nilsson	$\sigma_{exp,i}$ [mb]
$5/2^-_1$	0.04	0.20	$4.4(3)_{stat}(^{+0}_{-1.5})_{syst}$
$7/2^-_1$	3.25	1.80	$3.0(2)_{stat}(^{+0}_{-1.5})_{syst}$
$*7/2^-_2$	0.71	1.69	–
$*3/2^-_1$	0.13	0.20	–
$9/2^-_1$			$0.5(1)_{stat}(5)_{syst}$
$11/2^-_1$			$0.36(6)_{stat}(^{+0.45}_{-0.36})_{syst}$
?			$0.7(2)_{stat}(7)_{syst}$

Liu *et al.*, PLB **784**, 392 (2018).
C. Porzio, HLC *et al.*, to be published.

Quenching in One-Nucleon Knockout on Light Nuclear Targets

Now well-established systematics for knockout on Be/C targets

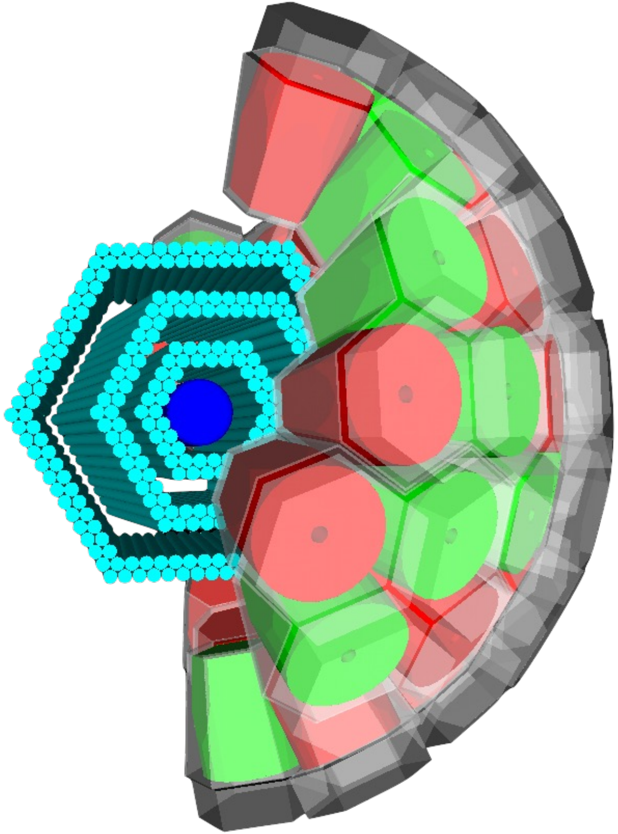
- Most recently in 2021 inclusive one nucleon removal cross-sections were tabulated in relation to consistent eikonal model + shell model calculations
- Systematic trend of R_S with ΔS seems well-established (though still with significant scatter)
- This correlation is now used* in interpreting the comparison of experiment with theory



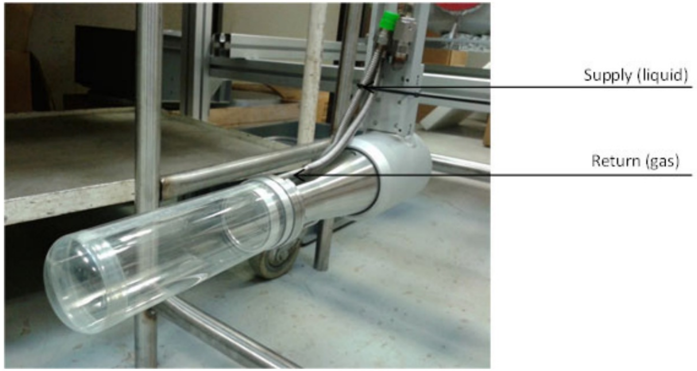
Tostevin and Gade, Phys. Rev. C **103**, 054610 (2021).

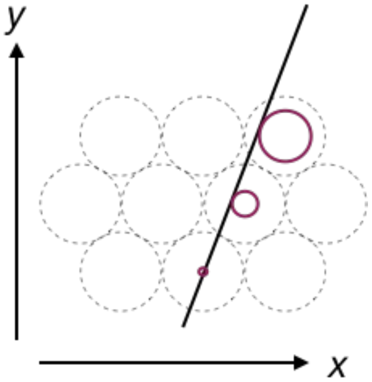
* A controversial issue…

Extended Proton Tracking Target to Maximize Luminosity



- Take the MINOS LH_2 target (developed by A. Obertelli *et al.*) as inspiration
- An extended (5-15 cm) LH_2 cell will be surrounded by a compact configuration of straw-tube (small diameter gas counters) detectors for proton detection and vertex reconstruction





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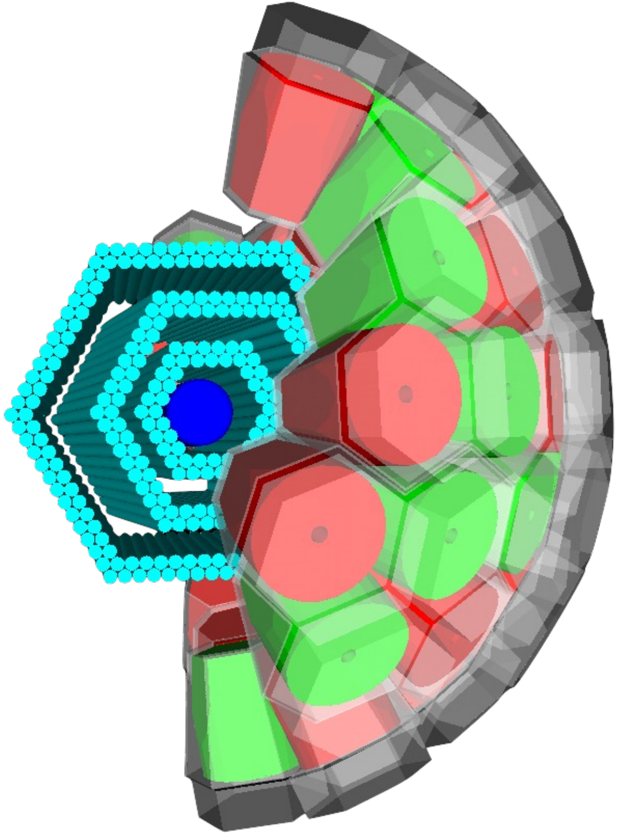
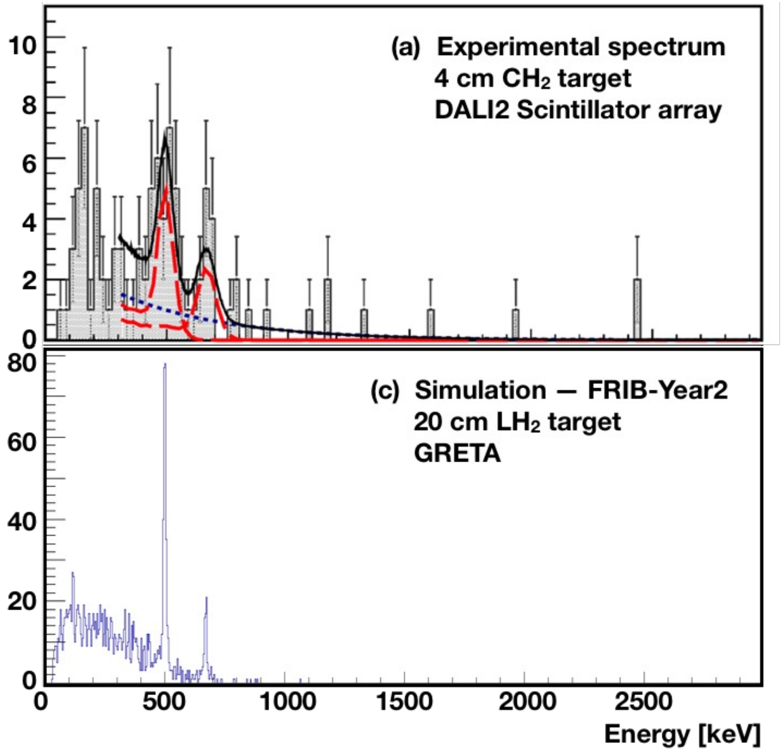
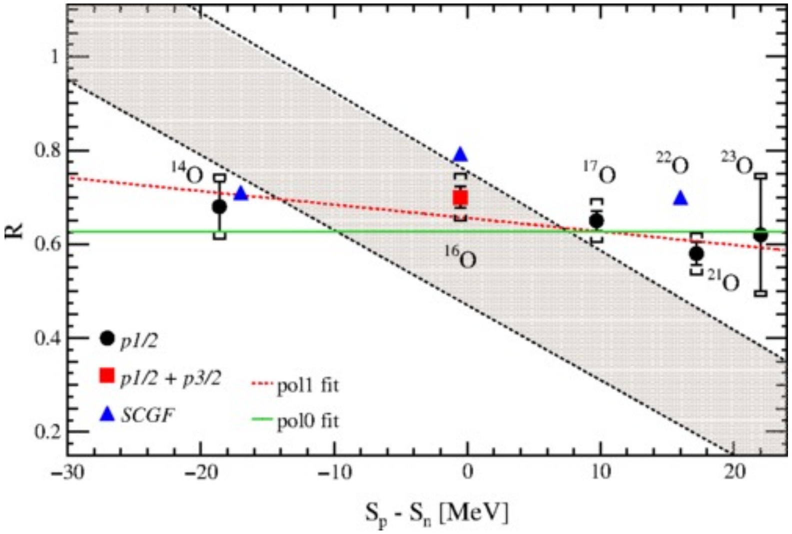
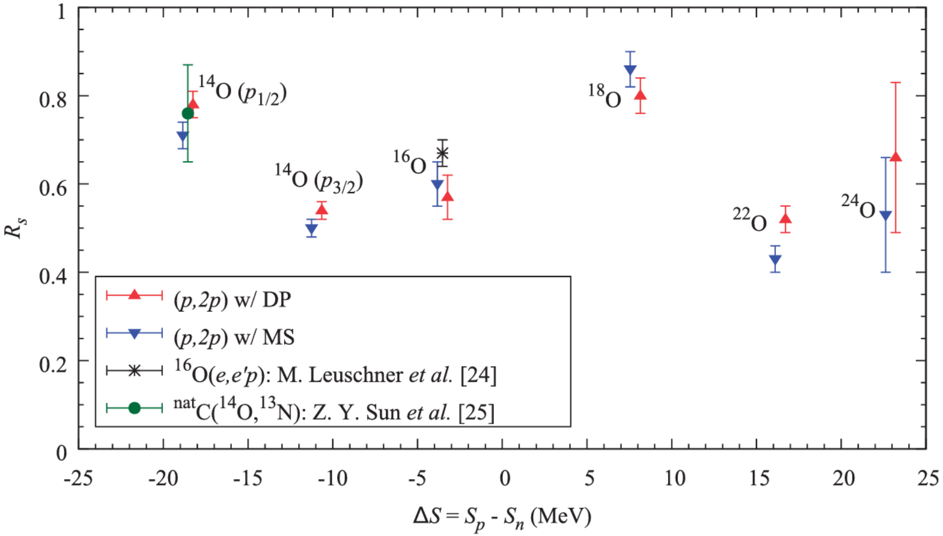




Quenching in Proton Target Nucleon Removal Reactions

First systematic studies in 2018 – the (p,2p) in the O isotopes





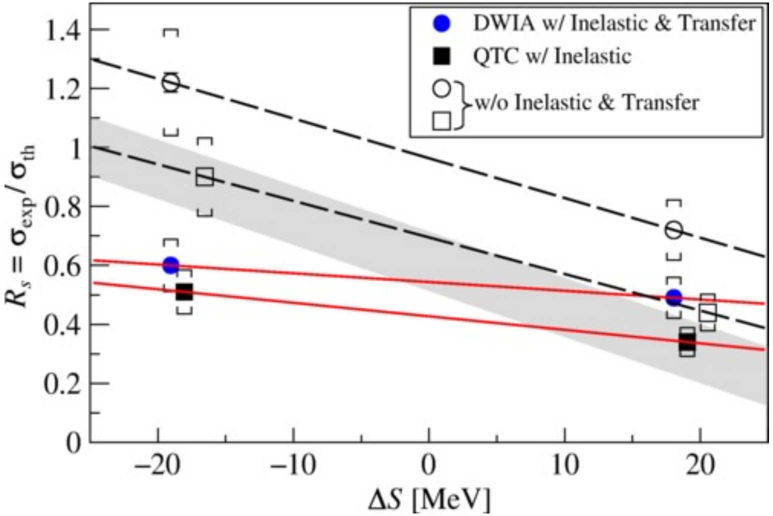
- Results from both GSI and RIBF of (p,2p) seem to show a relatively flat trend of R_S with ΔS
- Reaction theory is based on eikonal model with inclusion of multiple scattering treated through DWIA with a complex optical potential

L. Atar *et al*., Phys. Rev. Lett. **120**, 052501 (2018).
S. Kawase *et al*., Prog.Theor.Exp.Phys. **021D01** (2018).

Quenching in Proton Target Nucleon Removal Reactions

Additional data from RIBF in the O isotopes

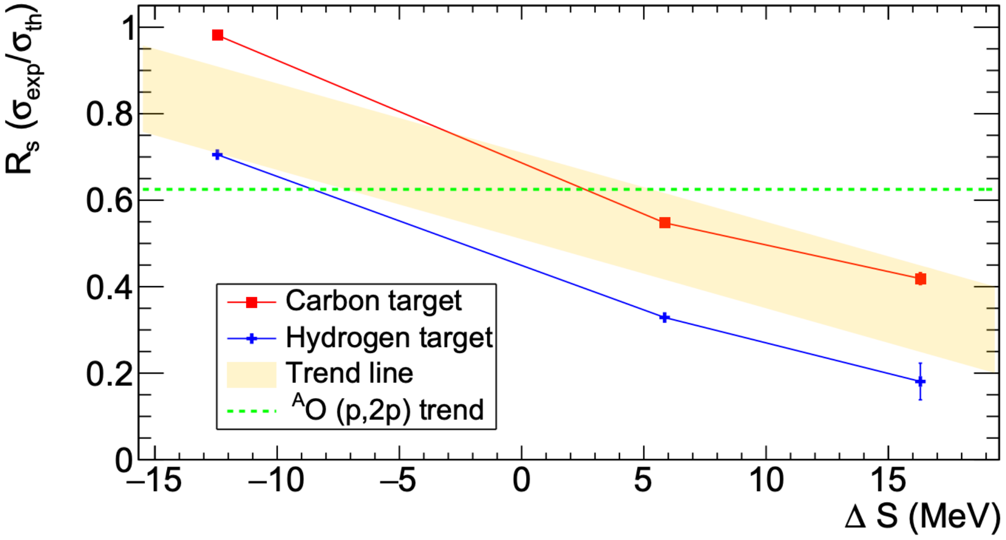
- Recent study explored (p,2p) and (p,pn) on ^{14}O at ~100MeV/nucleon (RIBF)
- Appears to agree with a flat trend (consistent with previous O results) when contributions from inelastic scattering and transfer reactions are included; without these contributions, is consistent with the trend observed for KO on Be/C targets



T. Pohl *et al*., Phys Rev. Lett. **130** , 172501 (2023).

Quenching in Proton Target Nucleon Removal Reactions

Measurement in the Ca isotopes on both C and H targets



- Measurement at RIBF studied proton removal with both C and CH_2 targets on ^{38,48,54}Ca
- Eikonal reaction theory, including inelastic scattering contributions, shows a strong trend of R_S with ΔS for both C and H targets
- Not completely clear what to expect for H targets – need to get a handle on this experimentally, but also from the theory side

A. Frotscher, HLC, *et al*. to be published.

Coulomb Excitation and Proton Inelastic Scattering

Better under control, but then there are effective charges…

- Intermediate energy Coulomb excitation is understood from the theory – challenge is separating the nuclear from the Coulex contribution, but this is on the experimental side
- Combining Coulex with proton inelastic scattering can determine M_n/M_p

dependent on coupled channels calculation (optical potential)

$$\frac{M_n}{M_p} = \frac{b_p}{b_n}\left[\frac{\delta_{(p,p')}}{\delta_p}\left(1 + \frac{b_n}{b_p}\frac{N}{Z}\right) - 1\right]$$

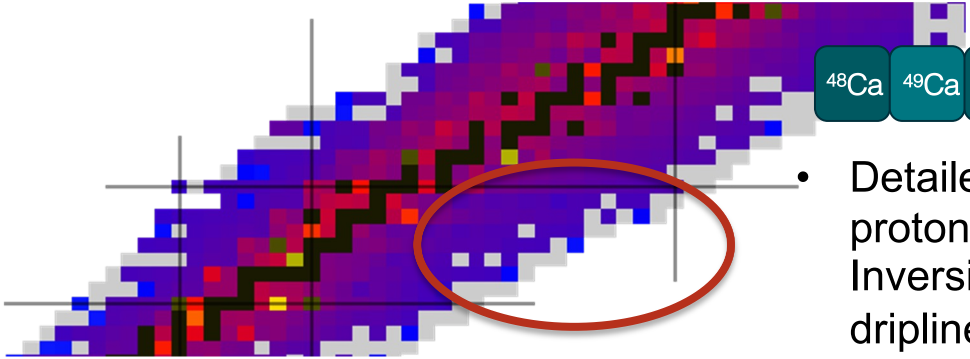
ratio of sensitivities to proton scattering

- Comparison with theory M_n/M_p requires assumption of core polarization / effective charges

Outline

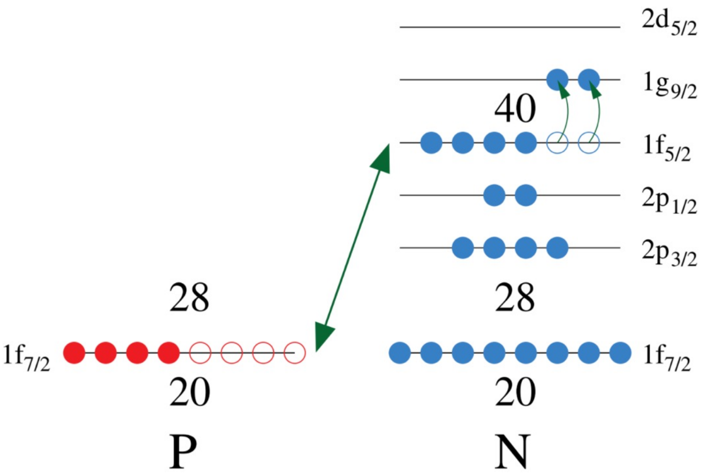
- Nucleon knockout
  - KO on Be/C targets
  - (p,2p)/(p,pn)/… on LH_2 target
- Coulomb excitation and inelastic proton scattering
- Where on the Segre chart?

Mapping Out N=40 to N=50 and Pushing Toward ^{60}Ca

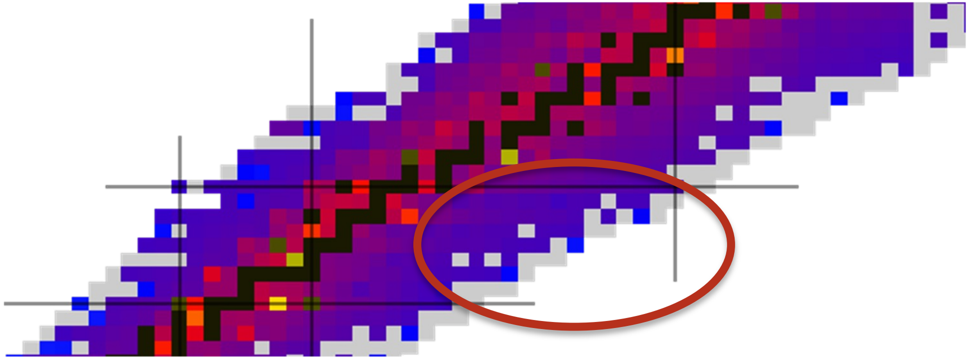


^{48}Ca ^{49}Ca ^{50}Ca ^{51}Ca ^{52}Ca ^{53}Ca ^{54}Ca ^{55}Ca ^{56}Ca ^{57}Ca ^{58}Ca ^{59}Ca ^{60}Ca …

- Detailed evolution of single-particle orbitals with proton/neutron number defines the N=40 Island of Inversion, and impacts ($\nu g_{9/2}$) the location of the dripline in the Ca isotopes
- Structure near the Ca isotopes may also be sensitive to **impacts of 3N forces**
- Out to N=50 – ^{78}Ni should be doubly-magic, but near N=40 Ni have shape coexistence



Mapping Out N=40 to N=50 and Pushing Toward ^{60}Ca



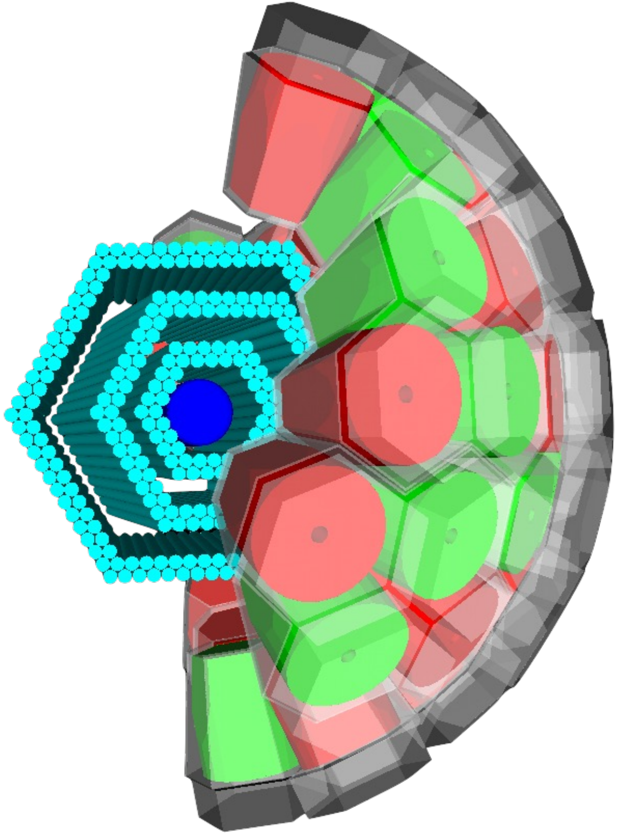
Nucleon Knockout

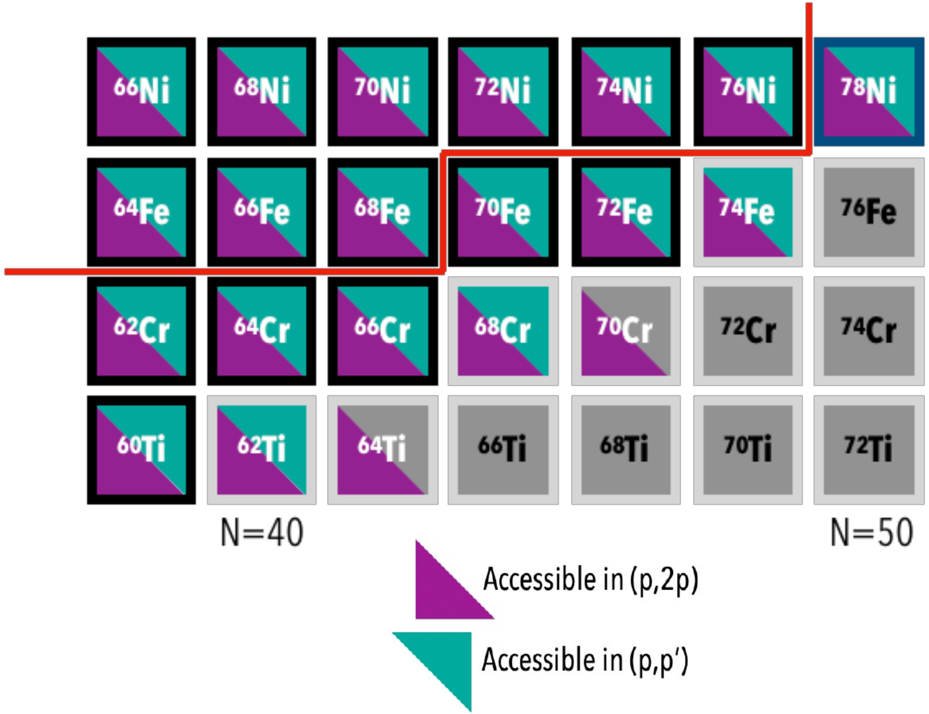
- In-beam γ-ray spectroscopy can map out evolution of single-particle states
- At NSCL -1p knockout has been performed up to ^{66}Fe/^{65}Mn – this can be extended substantially
- **10kW – up to ^{68}Fe; 20kW – up to ^{70}Fe; 400kW – as far as ^{74}Fe**
- With 400MeV upgrade and LH_2 target, will reach **^{60}Ca** via (p,3p) or possibly (p,2p)

Coulomb Excitation

- The degree of collectivity (e.g. B(E2) in even-even nuclei) helps to define nuclei in vs. outside of the N=40 Island of Inversion
- Intermediate energy Coulomb excitation can reach out to **^{70}Fe now (10kW)** to help delineate the limits of the region
- **Ultimately reach to ^{74}Fe (400kW)**

Extended Proton Tracking Target to Maximize Luminosity





^{66}Ni	^{68}Ni	^{70}Ni	^{72}Ni	^{74}Ni	^{76}Ni	^{78}Ni
^{64}Fe	^{66}Fe	^{68}Fe	^{70}Fe	^{72}Fe	^{74}Fe	^{76}Fe
^{62}Cr	^{64}Cr	^{66}Cr	^{68}Cr	^{70}Cr	^{72}Cr	^{74}Cr
^{60}Ti	^{62}Ti	^{64}Ti	^{66}Ti	^{68}Ti	^{70}Ti	^{72}Ti

Accessible in (p,2p)

Accessible in (p,p′)

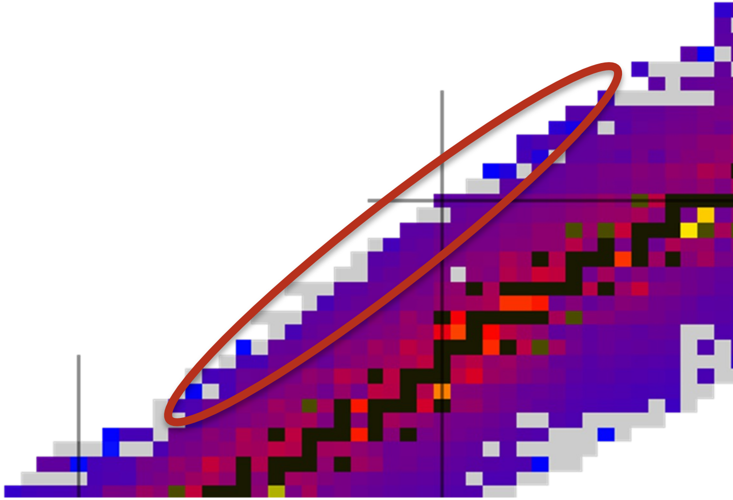
- Extends experimental reach by 1-2 neutrons for each isotopic chain

N=Z

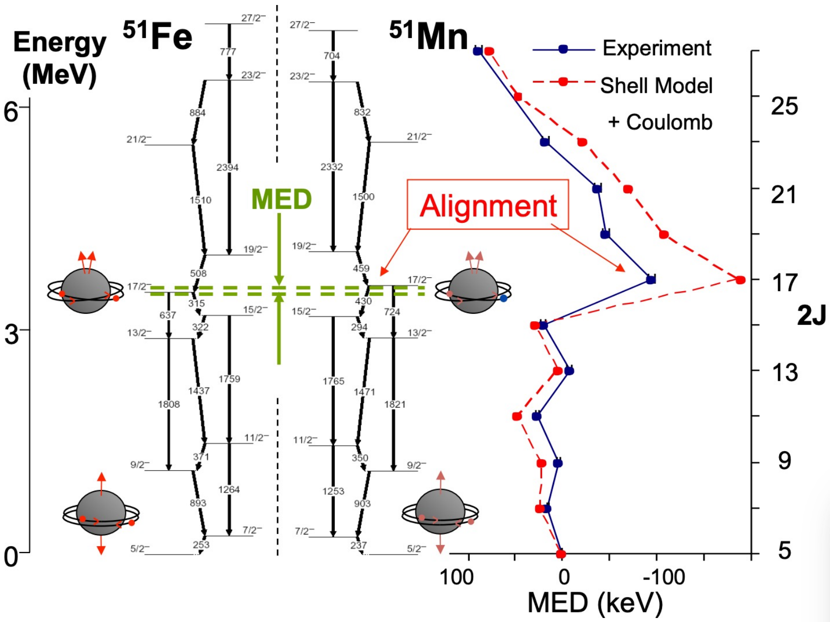
- The physics opportunities near N=Z are compelling
    - Studies of mirror symmetry can be extended within the fp shell
    - Island of inversion near ^{80}Zr (N=Z=40)

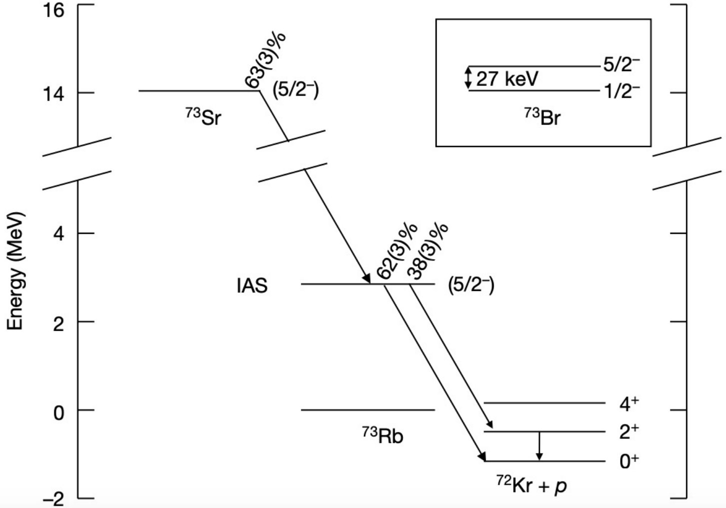
- These nuclei are accessible, thanks to ^{124}Xe and ^{238}U primary beams

- This is a **challenging region experimentally** though, with strong momentum tails from more stable fragments contaminating the beams produced – not easy, but a promising region with future technical development



N=Z





Effort has focused in the sd and lower fp shells to explore mirror systems looking for isospin non-conserving terms – e.g. J=2 anomaly


Article

Mirror-symmetry violation in bound nuclear ground states

https://doi.org/10.1038/s41586-020-2123-1

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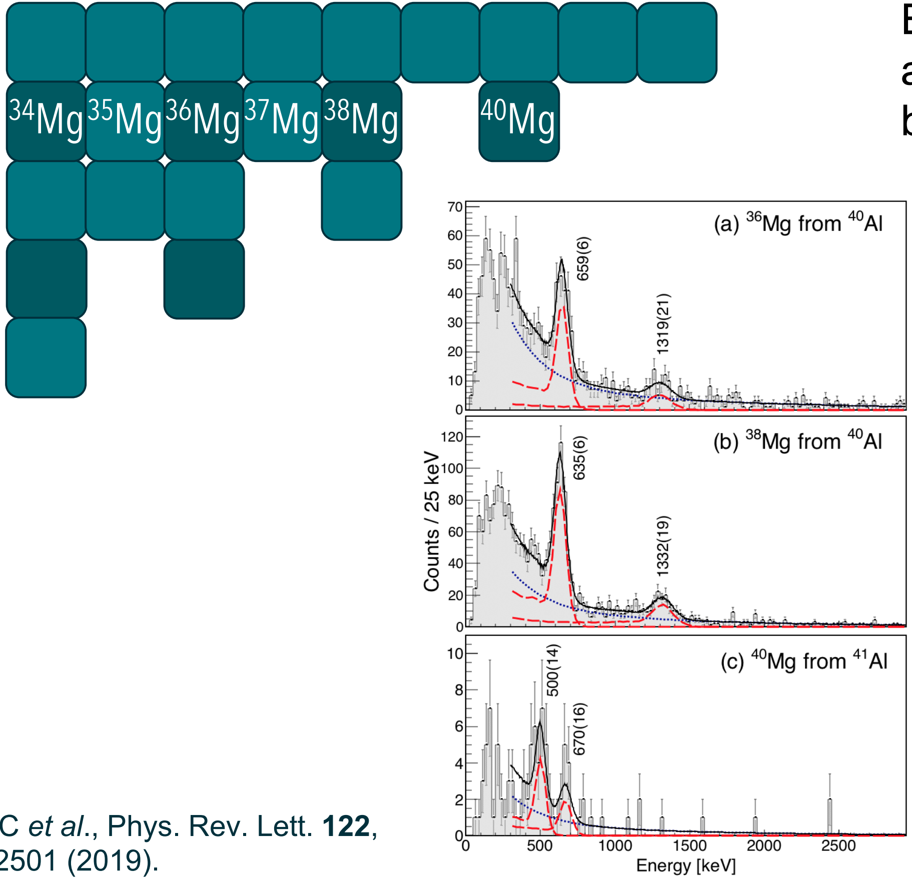
D. E. M. Hoff[1✉], A. M. Rogers[1✉], S. M. Wang[2], P. C. Bender[1], K. Brandenburg[3], K. Childers[2,4], J. A. Clark[5], A. C. Dombos[2,6,7], E. R. Doucet[1], S. Jin[2,7], R. Lewis[2,4], S. N. Liddick[2,4], C. J. Lister[1], Z. Meisel[3], C. Morse[1,9], W. Nazarewicz[6,8], H. Schatz[2,6,7], K. Schmidt[2,7,10], D. Soltesz[3], S. K. Subedi[3] & S. Waniganeththi[1]

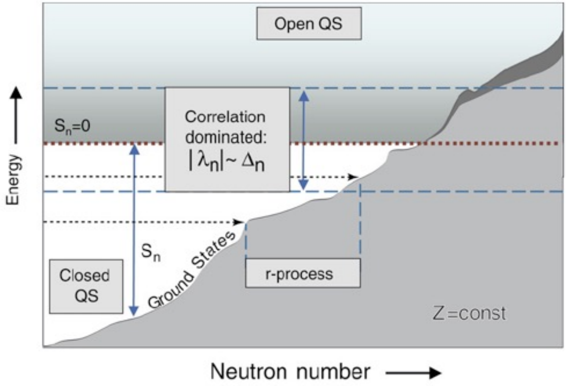
Warner *et al*., Nature Physics **2**, 311 (2006).

N=28 and the Role of the Continuum in Nuclear Structure



Explore properties of weakly bound nuclei and ask what happens in the transition from well-bound to weakly-bound “open” systems

⇒ Due to weakly bound levels
- low l levels (s, p) → extended wavefunctions (“halos”)
- changes in pairing due to surface diffuseness
- valence nucleons can become decoupled from the core
- coupling to continuum states

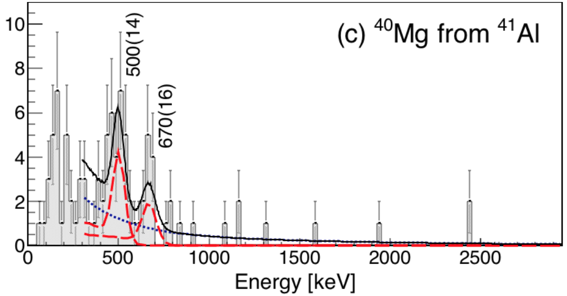


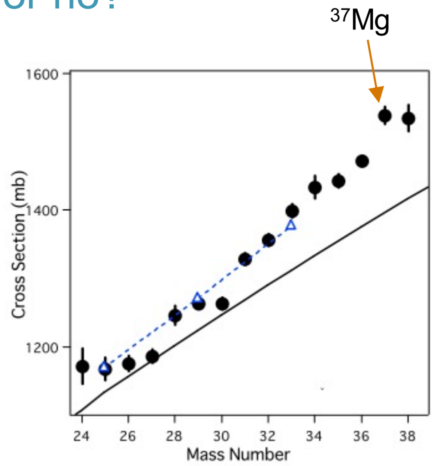
HLC *et al.*, Phys. Rev. Lett. **122**, 052501 (2019).

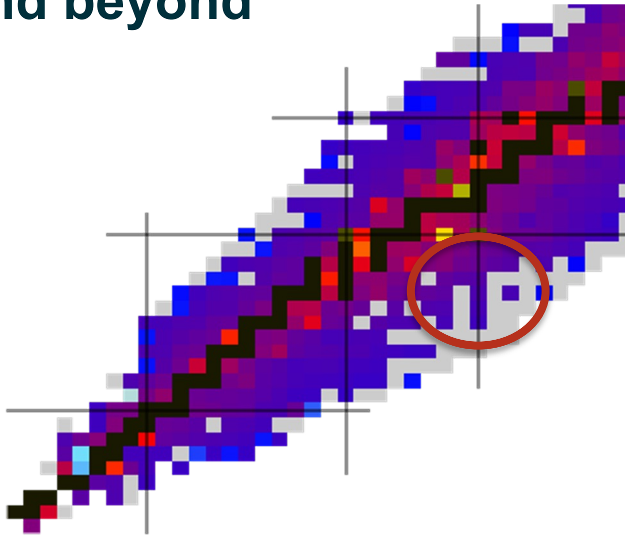
Pushing Toward the Neutron Dripline – Z=12 and beyond

^{40}Mg reaction cross-section – halo or no?

First spectroscopy in ^{40}Mg shows a surprising structure – could the spectrum be evidence of weak binding / halo structure?

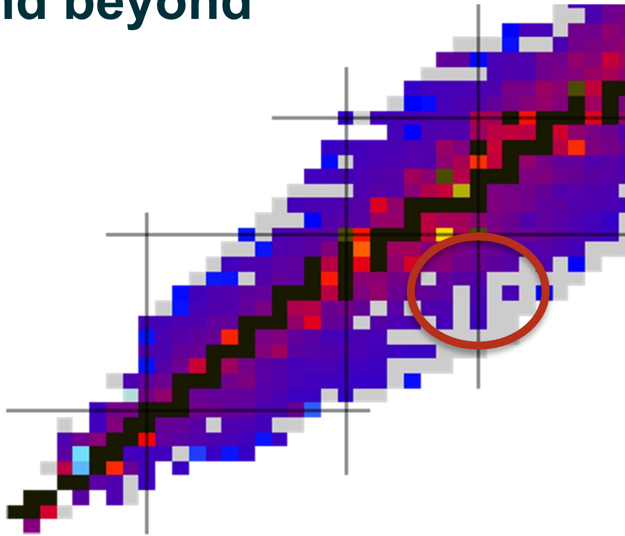




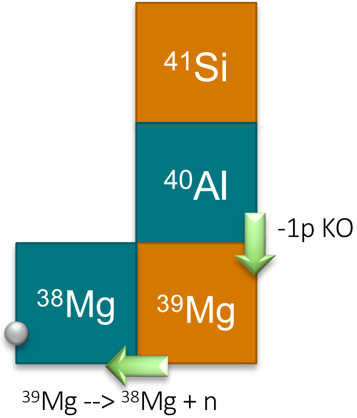


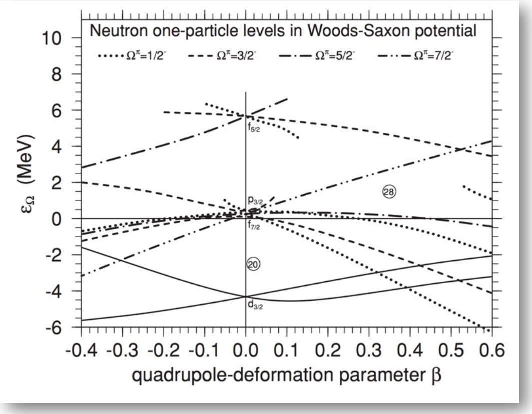
- A total reaction cross-section measurement for ^{40}Mg will answer the question of whether there is a halo or not
- Combined with a TOF mass measurement, the separation energy can be established

Pushing Toward the Neutron Dripline – Z=12 and beyond



- There may be a wide range of experiments in this region –
  - precision mass measurements toward N=28
  - β-decay extending all the way to decay of ^{40}Mg and beyond N=28 above Mg
  - Single-nucleon knockout studies (e.g. into ^{38}Mg)
  - Coulomb excitation (intermediate energy) – ^{42}Si
  - **Invariant mass measurement in ^{39}Mg with MoNA-LISA**





Open Questions:

- What is the neutron separation energy of ^{39}Mg?
- What is the ground-state deformation?
- Is there a ground-state halo structure arising from the *p*-orbital occupation?
- How large is the *N* = 28 gap between the *f* and *p* orbitals?

Additional opportunities:

- Unbound states in ^{40}Mg (^{41}Al -1p)

Summary

- In-beam direct reactions and gamma-ray spectroscopy were a work-horse at NSCL and will continue to be at FRIB

- Direct nucleon knockout specifically is a key tool, with access to the wavefunction overlaps of the beam and reaction residue
    - Quenching of experiment cross-sections relative to the calculations remains an incompletely-understood challenge

- These techniques will be applied across the nuclear chart – focus in the near future at *N*=28, *N*=40 above $_{20}$Ca (or along Ca), along *N*=*Z*

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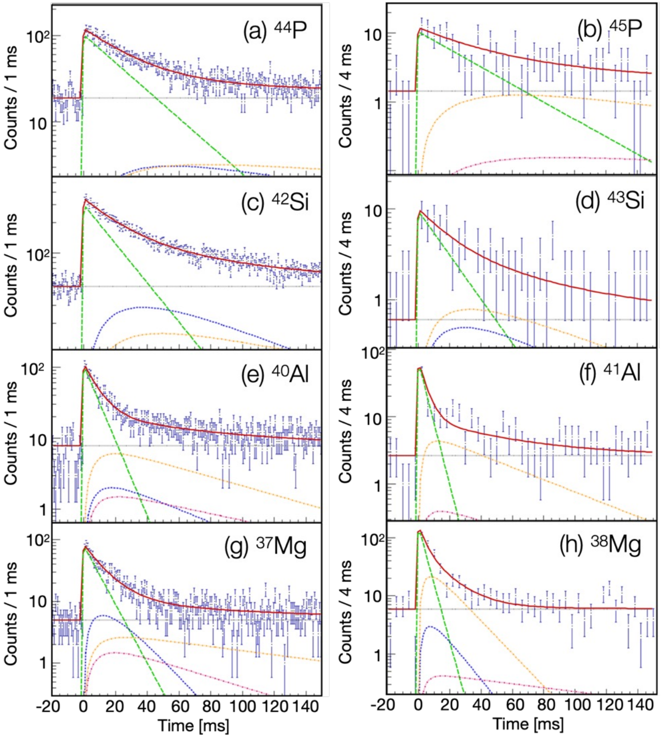
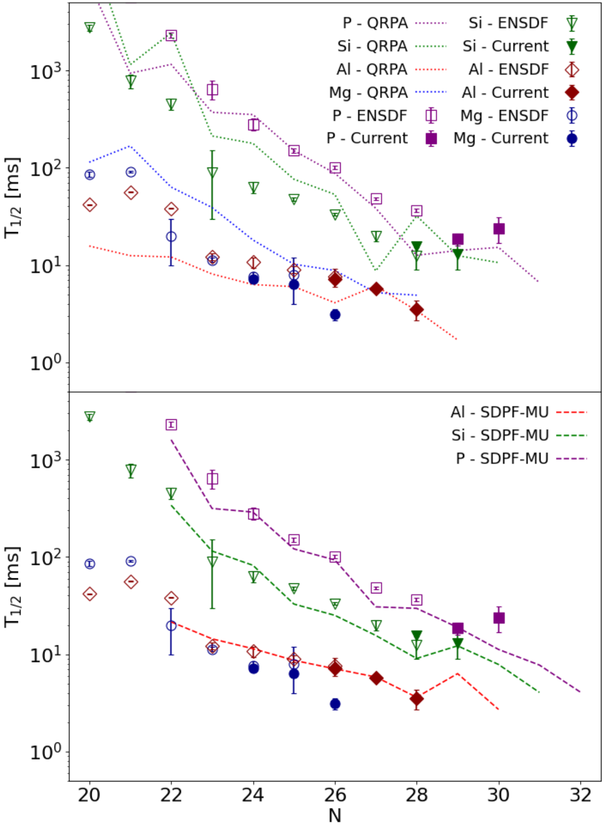
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contracts No. DE-AC02-05CH11231 (LBNL).

One last comment…

Current Results Without Complete Theory…

E21062: Decay Near *N*=28

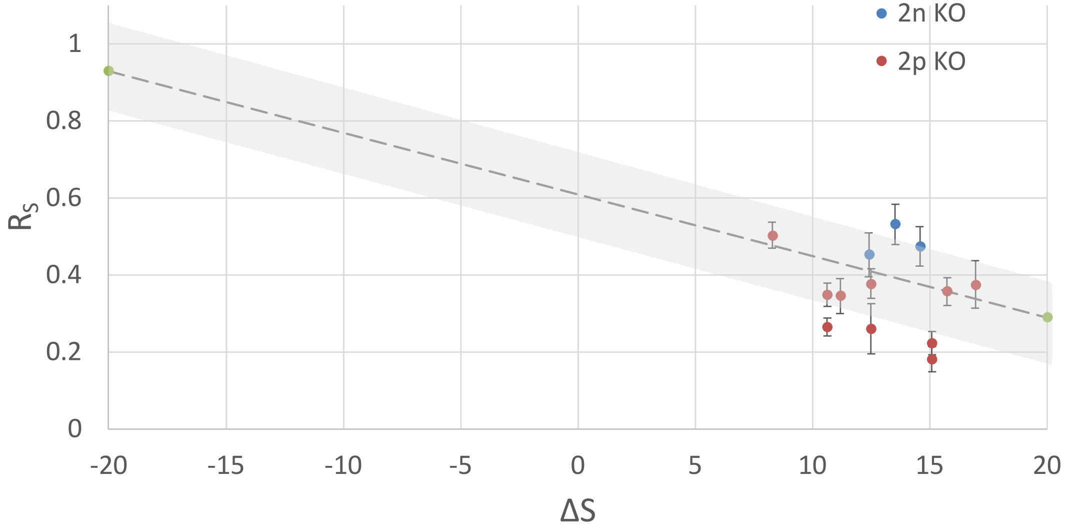




Thank you!

Two-Nucleon Removal?

More limited data, even less clarity?



- With very little in terms of data, one could believe that the 2-nucleon removal follows a similar trend to 1-nucleon removal in terms of R_S as a function of ΔS
- Or we could say we have no idea what is going on at this time
- What do we actually expect?
  - Structure input is two-nucleon amplitude (TNA)
  - Reaction theory is similar to 1 nucleon knockout… expect R_S^2 ? Or is it more complex than this?

Acknowledgements

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